High Resolution Optical Spectroscopy

Introduction

This experiment will allow you to learn a specific optical technique with applications over a wide variety of phenomena. You will use a commercial spectrometer (a very common piece of equipment in research labs) to obtain the emission wavelengths of particular elements (e.g. mercury, sodium, hydrogen and deuterium) as well as to compare the outputs of gas and solid state lasers. You will be able to analyze the accuracy and precision of this tool by comparing your measured wavelengths with the corresponding accepted values.

Experimental Setup

Required Equipment

Double-monochromator spectrometer SPEX 1404 with a cooled photomultiplier (PMT) detector
White lamp
10-mW helium-neon laser
486 nm laser
Mercury, sodium and hydrogen-deuterium lamps
Ground glass diffuser
Neutral density filters

The SPEX 1404 is a commercial double grating spectrometer (see Appendix 2). Light enters the first slit, hits a mirror that focuses it (the light) onto a diffraction grating. Light from the diffraction grating hits a second mirror and is focused to the second (internal) slit. The light then hits another mirror, grating and mirror combination and is focused onto the exit slit (Figure 1). Good initial values are 100 microns for entrance and exit slits and 1 mm for the center slit.
- With a light source near the entrance slit and no power supplied to the photomultiplier tube (PMT), remove the top of the spectrometer and observe the dial reading at which the slit has its minimum width. Follow the light path through the spectrometer with a white piece of paper.

NOTE: The spectrometer was designed for a 1200 groove/mm grating; to enhance resolution we have installed one with 1800 grooves. Hence, the true wavelength at which the grating is interfering constructively is $2/3$ the number shown on the counter; conversely the value on the counter is 50% greater than what appears on the screen at the beginning of the scan.

Data acquisition for the SPEX spectrometer is done with a Labview program (Fig. 5). The
spectrometer is driven with a stepper motor that rotates the gratings. It has a drive unit and a computer interface unit. Both of these need to have power. The spectrometer output is collected with a cooled photomultiplier (PMT) detector whose output is first fed to a preamplifier (Stanford model 440), then to the Stanford model SR 400 Gated Photon Counter and finally to the pc. The Labview program is in a directory c:/LabviewVI as well as the desktop. The spectrometer program moves the spectrometer, receives the output from the Photon Counter and stores both in a file as two columns of ASCII.

It is claimed that the line width of the HeNe emission spectrum is 1.5 MHz. Unfortunately this is not directly useful in telling you whether the line width is greater or less than the claimed resolution of the system. For any wave it is well known that the product of the wavelength and frequency is its propagation velocity. For the HeNe, calculate the corresponding line width (in wavelength). Is this greater or less than the advertised resolution of the spectrometer?

Operation of the spectrometer system is explained in Appendix 1.

**Experimental Procedure**

1) Begin your investigations by dispersing the light from either a helium-neon (He-Ne) laser (wavelength 632.8 nm) or a small mercury lamp (wavelength 546.1 nm). The 10-mW HeNe laser has enough power to damage the preamp, hence use a neutral density filter to reduce this power or diffuse the beam with a ground glass. Observe and plot peak FWHM (Full Width at Half Maximum; “Half width”) and signal integrated intensity as a function of slit width. Check wavelength accuracy by comparing to NIST value.

2) The resolution of the spectrometer is claimed to be 0.006 nm and the dispersion to be 0.44 nm/mm of slit width. The latter means that if you have both slits set to 1 mm, you should be able to resolve two peaks that are 0.44 nm apart; if you set the slits to 0.1 mm, you should be able to resolve two peaks 0.04 nm apart, etc. Test this “model” using the H2-D2 emission as input. Compare the measured sodium doublet wavelengths with the accepted ones [1].

3) The hydrogen-deuterium lamp has lines near 656 nm with about 0.1 nm separation. Based on manufacturer’s specification for dispersion, estimate the widths of the entrance and exit slits, and the number of steps required to resolve them. Take data to test your estimates; indeed, take spectra as a function of slit width to test the manufacturer’s claim. Compare your measured hydrogen and deuterium emission wavelengths with the accepted ones [1]. Is this an awesome piece of equipment or what?

Deuterium is an isotope of hydrogen whose nucleus contains one proton and one neutron. In the Balmer experiment your classmates are learning that \(\frac{1}{\lambda} = R_\infty \left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right)\) where \(R_\infty\) is the Rydberg constant assuming the nucleus has infinite mass. For the red line in the hydrogen and deuterium spectra \(n_i = 3\) and \(n_f = 2\). \(R_\infty = \frac{me^4}{\varepsilon_0^2 ch^3}\) But this assumes that the
nuclear mass is infinite. Accuracy of the calculated wavelength is improved by correcting \( R_\infty \) with the reduced mass: 
\[ R_H = \frac{R_\infty}{\left(1 + \frac{m_e}{m_p}\right)} \]
where \( m_e \) is the mass of the electron and \( m_p \) is the mass of the proton. There is an equivalent expression for the reduced mass and corrected Rydberg constant of the deuteron. From the fundamental constants in the Rydberg equation, calculate the theoretical wavelength in the hydrogen spectrum. From your measurements of the difference between the emission wavelengths of hydrogen and deuterium, calculate the mass of the \textit{neutron}. Compare your result to the published value. To how many significant digits do you expect your result to be correct? Is there a significant discrepancy between your result and the published value? Is this cool or what? Are we having fun yet?

4) This class is about testing models. What model(s) can you test with the equipment you have been given?

5) A huge fraction of the work to date has centered on error analysis. What are the sources of error in your observations? What are your estimates of the errors in your measurements?

References

Appendix 1: Spectrometer operation

The High Resolution Spectrometer

Fig. 1: Spex 1404 spectrometer layout

Fig. 2: Preamplifier and thermoelectric cooler for PMT (PhotoMultiplier Tube)
Fig. 3: PMT high voltage supply and gated photon counter

Fig. 4: Desktop on system control computer
Fig. 5: Labview interface. Lock-in amplifier/single photon counting switch, scanning parameter input and filename entry option locations

Fig. 6: Popup showing where the software thinks the spectrometer gratings are set. Check the value displayed on the side of the spectrometer to assure that it agrees with what the software shows.

Appendix 2: Monochromators and spectrometers (generic information originally
intended for the Photoelectric experiment)

- How does the monochromator work?

Remove the lid and look at the inner workings, with the room lights off but the lamp on. Follow the beam path with a piece of paper. DO NOT, UNDER ANY CIRCUMSTANCES WHATSOEVER, TOUCH THE GRATINGS OR THE MIRRORS.

- What is the difference between a monochromator and a spectrometer?

They are basically the same piece of equipment but used differently. A monochromator selects a narrow distribution of wavelengths/energies/frequencies from a broad distribution for use in some application. The grating is adjusted to a fixed angle, which gives the desired output wavelength/energy/frequency. It is a light source of adjustable, nominally “monochromatic” light; i.e. the output is light of a “known wavelength”.

The output of a spectrometer is information: a detector is attached to the exit slit of the same piece of equipment and the grating is scanned through an angle. As the grating is scanned in angle (in time), the various wavelengths in the spectrum of light incident on the entrance slit are scanned across the exit slit and detector [2]. By correlating the intensity of light incident on the exit slit to the grating angle (as a function of the same time), one can back-calculate the intensity of light incident on the entrance slit as a function of its wavelength/energy/frequency. The spectrometer tells you the intensity distribution of the emission from some light source.

The SPEX 1404 is a double-monochromator spectrometer. It has two monochromators in series in order to reject the unwanted and intense incident light (“stray light”) into its output [3].
Appendix 3. Spex 1404 manufacturer’s specifications

7.1 Specification

OPTICAL
Mount: Modified Czerny-Turner, additive dispersion
Focal length: 0.85m
Aperture: f/7.8
Mirrors: MgF₂ overcoated, aluminized
Slits: four straight, bilaterally adjustable
Max. width, mm: 3 at entrance and exit, 5 at center
Max. height, mm: 20

Gratings, Ruled
Area, mm
Density, grooves/mm
Blaze, nm
Range
102 x 128 or 128 x 102
8-3600
300-112500

Gratings, Holographic
Area, mm
Density, grooves/mm
Range
110 x 110 or 110 x 128
1800, 2400, 3600
UV or Visible

Spectral Purity¹, 1/λ₀
Spectral Coverage
Dispersion at 514.5 nm
Resolution, Hg 579.1 nm (FWHM)
Readout, 5 digits
Accuracy
Repeatability
<10⁻¹⁴ at >Δ20 cm⁻¹
31000-11000 cm⁻¹
10 cm⁻¹/mm
0.15 cm⁻¹
cm⁻¹ and Δcm⁻¹
= 1 over 10000 cm⁻¹
= 0.2 cm⁻¹

Model 1403
Model 1404
≤ 0.05 nm
nm
≤ 0.1 over 500 nm
= 0.03 nm

Notes:
1. Where applicable, specifications assume operation with a pair of 110 x 110 mm holographic gratings, 1800 groove/mm, set to order 1. Ambient temperature stability is also assumed. To maintain performance specifications in surroundings with constant barometric pressure but slow ambient temperature changes between 18 and 25°C, the 1470 Thermostating accessory provides a preset 24°C temperature of the instrument.
2. With protected silver mirrors (optional at higher price), luminosity enhancement of about 40% may be realized below 25000 cm⁻¹ (above 400nm).
3. With 514.5 nm Ar⁺ laser source, bandpass 0.25 cm⁻¹ (0.008 nm).
4. Counter reads correctly for 1800 groove/mm gratings in 1403, 1200 grooves/mm in 1404.